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UNITED STATES LETTERS PATENT

FOR

APPARATUS AND METHODS FOR USING A SURFACE OSCILLATOR AS A DOWNHOLE SEISMIC SOURCE

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BACKGROUND OF THE INVENTION

This application claims priority from United States Provisional Application 60/262,992 filed on January 19, 2001.

1. Field of the Invention

The present invention relates to the field of acquiring seismic data and in particular to a system for acquiring seismic data using a surface actuated downhole source.

2. Description of the Related Art

Downhole seismic sources are used to determine the geological characteristics of the underground strata surrounding the borehole. The objective of such sources is to create seismic waves which propagate into the surrounding formation. Receivers, such as geophones, detect the seismic waves after they have traveled through the geologic strata. Processing of these received waves can be used to determine the characteristics of the geologic formation including those of the various reflecting strata interfaces.

Various receiver techniques are used with downhole seismic sources. These techniques include placing the receivers in adjacent offset wells, also known as cross-well tomography. In another technique, the receivers are placed on the surface of the ground to detect the downhole generated signal. This is also known as reverse vertical seismic profiling ("RVSP"). In another technique, the receivers are co-located in the same wellbore as the downhole seismic source.

Conventional downhole seismic sources are usually suspended down a borehole from a cable which also provides power to operate the source and conveys various sensor signals associated with the source back to the surface. The electrical driving power available to such devices is usually limited to a few kilowatts by cable constraints. This power constraint limits the available downhole signal strength and produces signals which have limited detectable range within the formation. These sources are typically driven at their maximum power levels to maximize the transmission distance. In addition, these sources do not use the received signals in a closed-loop system to adjust the generated signal to maximize the received signal. Thus there is a need for a seismic system which can generate sufficient power downhole to extend the detectable range of the generated signals. This system should be capable of working in a stand-alone, open-loop manner and in a closed-loop manner utilizing the received signals to adjust the generated signal to maximize the detection range.

SUMMARY OF THE INVENTION

The present invention provides an improved system for generating downhole seismic signals by overcoming previous limitations as to received signal strength and closed loop control of the vibratory source to maximize the received signal.

In one embodiment of the invention, a vibratory source is coupled by a tubular string to a downhole anchor. The vibratory source is powered by a power source which can be a hydraulic, electric, or pneumatic system. Load and motion sensors are mounted on the tubular string both downhole and at the surface, and provide signals to a surface control unit for use in feedback control of the vibratory source. Seismic sensors, such as geophones, may be deployed on the

surface, in offset wells, or in the same well as the source. These signals are transmitted back to the control unit and may be used to control the vibratory source so as to maximize the received signals.

In another embodiment, the surface vibratory source imparts axial motion to a tubular string which is attached to a downhole hammer apparatus such that axial motion of the tubular string causes the downhole hammer to impart a broadband signal which is transmitted into the surrounding reservoir formation.

In one aspect of the invention a method of generating a downhole seismic signal in a wellbore is presented which comprises (i) providing a vibratory source at a surface location; (ii) coupling the vibratory source to the upper end of a tubular string, anchoring the tubular string at a selected downhole location; and (iii) operating the vibratory source in an axial vibration mode to cause axial vibratory displacement of the upper end of the tubular string thereby transmitting the vibrational motion to the anchor and inducing a seismic signal into the surrounding formation.

An alternative method comprises (i) measuring parameters of interest and transmitting the measurements to the surface control unit; and (ii) controlling the vibratory source based on the measurements of the parameters of interest.

Examples of the more important features of the invention have been summarized rather broadly in order that the detailed description thereof that follows may be better understood, and in order that the contributions to the art may be appreciated. There are, of course, additional

features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.

BRIEF DESCRIPTION OF THE DRAWINGS

For detailed understanding of the present invention, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

Figure 1 is a schematic illustration of a system for generating downhole seismic waves in a reservoir according to one embodiment of the present invention; and

Figure 2 is a alternative arrangement of a downhole seismic source according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to **Figure 1**, the system is schematically illustrated. The vibratory source **15** is attached to support cable **65** and supported by support derrick **10**. The vibratory source **15** is clamped to the upper, free end of tubular string **40**. The tubular string **40** extends down the wellbore **55** to a location where it is desired to generate seismic waves in the reservoir formation **60**. The tubular string **40** has an anchor **50** attached to the downhole end of the tubular string **40**. A number of commercially available devices can serve as the anchor **50**, including, but not limited to, a resettable packer, a resettable and retrievable bridge plug, a tubing hanger, or any other suitable device known in the art. The anchor **50** is activated at the desired downhole location so that the lower end of the tubular string **40** is essentially constrained from moving axially. Axial oscillation of the upper, free end of tubular string **40** is vibrationally transmitted down tubular string **40** to the constrained lower end and is transferred through the anchor **50** as primarily shear waves into the reservoir formation **60**. The anchor **50** may be retrieved and reset at multiple downhole locations to provide seismic input to the formation at multiple locations.

Alternatively, multiple fixed anchors(not shown), such as a tubing hanger, may be permanently located at multiple locations in the wellbore 55 to provide a known location for taking seismic data at different times for comparison and analysis of formation properties over time.

The surface located vibratory source **15** is powered by power source **30** which is controlled by a control unit **25**. The control unit **25** contains a processor (not shown) which may be may be a microprocessor, a microcomputer, or a computer with suitable capability to accept

sensor inputs and provide output control signals. The control unit **25** may also have mass data storage capacity. Such devices are well known in the art and are not described further.

Vibration sensor **20** is mounted on the vibratory source **15** and generates signals proportional to the vibrational motion of the vibratory source **15** which are transmitted to control unit **25**. Load sensor **21** is inserted in the tubular string **40** near the surface. Load sensor **21** generates signals proportional to the vibration force and the static force imposed on the tubular string **40** by the motion of the vibratory source **15** and by the weight of the tubular string **40**.

Vibration sensor **45** is mounted proximate the downhole anchor **50** and measures the characteristics of the downhole vibration imparted to anchor **50** and thus to the reservoir **60**.

Signals from the vibration sensor **45** are transmitted to the surface control unit **25** via sensor cable **35** which may be an instrument cable, a standard wireline logging cable, an optical cable or a combination cable having both electrical and optical capabilities. Alternatively, the signals from vibration sensor **45** can be transmitted by acoustic or electromagnetic techniques known in the art.

Load sensor **22** is inserted in tubular string **40** proximate to anchor **50** and measures the tension and compression loads imparted to the anchor **50** due to the vibratory motion of and weight of the tubular string **40**. Signals from the load cell are transmitted to the surface control unit **25** via sensor cable **35**. Alternatively, the signals from load sensor **22** can be transmitted by acoustic or electromagnetic techniques to the control unit **25**.

The control unit **25** is programmed to compare the signals from the surface vibration sensor **20** and the downhole vibration sensor **45** and signals from the upper load sensor **21** and the lower load sensor **22** to determine the transmissibility of power from the vibratory source **15** to the anchor **50**.

Seismic receivers **70a** - **70n** are mounted on the surface at a distance from the source borehole **1**. These receivers are typically geophones known in the art and sense the seismic signals imparted to the formation **60** by the system in borehole **1**. The receivers **70a** - **70n** may be deployed in predetermined patterns on the surface to best determine the subsurface characteristics. The signals from receivers **70a** - **70n** are transmitted to the control unit **25**.

Seismic receivers **80a** - **80n** are deployed in an offset borehole **2** and sense the seismic signals at different depths in the offset borehole. The signals from receivers **80a** - **80n** are transmitted to control unit **25**. There may be multiple sets of receivers **80a** - **80n** deployed in multiple offset boreholes proximate the source borehole **1**.

The signals from the receivers **70a** - **70n** and **80a** - **80n** may be processed either separately or together by the control unit **25** and the results used to modify the operation of the vibratory source **15** so as to improve the signal at the receivers **70a** - **70n** and **80a** - **80n**. Such modifications include but are not limited to changing the frequency of the vibratory source **15** and changing the vibration amplitude of source **15**.

In a preferred embodiment referring to **Figure 1**, the surface vibratory source **15** is a hydraulically driven device, such as Product No. 140-52 of Baker Oil Tools, a division of Baker Hughes Incorporated. This device is also described in U.S. Patent No. 5,234,056, which is incorporated herein by reference. Such a device provides a highly elastic support so as to provide for a very low impedance to vibration at the upper end of tubular string **40**. This vibratory source **15** is designed to vibrationally isolate the tubular string **40** from the support derrick **10**. This vibratory source **15** can provide a typical surface axial displacement of 1 to 2 inches.

In this embodiment, the power source **30** is a servo-controlled hydraulic system which can be controlled by the control unit **25** to vary the hydraulic fluid flow rate to the vibratory source **15** causing the vibratory source **15** to vibrate at a rate proportional to the flow rate thereby varying the frequency of axial vibration. The measurements of load from load sensors **21** and **22**, and of vibratory motion from vibration sensors **20** and **45** are transmitted to the control unit **25**. The load and vibration data are used to determine the power transmissibility from the surface to the downhole location. The load data is also used to limit the amplitude of vibration to safe levels. The control unit **25** also receives data from receivers **70a - 70n** and/or **80a - 80n**. This receiver data is used to modify the source signal so as to maximize the signal at the receivers. The source signal may be modified in a closed-loop real time mode or alternatively, the data may be processed and the source signal modified sequentially. The receiver signals may also be stored in memory or on permanent storage media for later processing.

In a preferred embodiment the control unit **25** may be programmed to generate a single frequency or alternatively it may be programmed to generate a swept frequency signal.

In another embodiment the signals from the same well receivers **90a - 90n** are transmitted to the control unit **25** and these signals are used to modify the source signal to maximize the signal received by **90a - 90n**. The signals from receivers **90a - 90n** may also be stored in memory by the control unit **25**. Those received signals may also be stored, in either analog or digital form, on permanent storage media suitable for retrieval and subsequent processing.

In yet another embodiment, the receiver signals are transmitted to a separate data storage system (not shown) for storage. The control unit **25** according to programmed instructions, uses signals from the load cells **21** and **22** and the vibration sensors **20** and **45** to control the source signal.

In still another embodiment, the source signal is controlled manually. The load sensors **21** and **22** and the vibration sensors **20** and **45** use stand-alone power and display readouts (not shown). The operator manually controls the vibratory source **15**.

An alternative anchor embodiment is shown in **Figure 2**, where the tubular string **40** is not axially fixed in the downhole location, but instead uses the cyclical axial motion to impact an anchored anvil to generate broadband seismic waves in the formation. The operation of the equipment on the surface is essentially the same. A slip anvil **100** is anchored to the borehole. The slip anvil **100** may be installed with techniques generally known in the art. The driver **110** is

attached to the bottom of tubular string **40** and moves axially with tubular string **40**. The driver **110** can be of a two-piece construction (not shown) so as to allow assembly with the anvil **100**. The driver **110** has tapered sections at each end of a reduced cross-section, such that each of the tapered sections alternatively impact corresponding sections of the anvil **100** as the tubular string moves alternatively up and down in response to the motion of the surface vibratory source **15**. The driver **110** creates axial and radial impact forces which are coupled through the slip anvil **100** into the reservoir formation **60** as seismic waves. These seismic waves project a broadband signal into the formation.

In one aspect of the invention a method for generating and receiving seismic waves is presented which includes the steps for (i) attaching a surface mounted vibratory source to a tubular string in a borehole; (ii) controlling the vibratory source with a surface control system and a programmed processor; (iii) anchoring the tubular string to the wellbore at one or more locations downhole; (iv) operating the vibratory source to generate seismic waves which propagate into the surrounding formation; (v) measuring the load on the tubular string at the surface and proximate the anchor; (vi) transmitting load and motion data to the processor; (vii) locating seismic receivers on the surface, in offset wells, or in the borehole with the source; (viii) transmitting the receiver data to the processor; and (ix) operating the processor, according to programmed instructions, to use the load data, the vibrational motion data, and the receiver data in a closed loop control mode to adjust the vibratory source in order to maximize the received signals

The foregoing description is directed to particular embodiments of the present invention for the purpose of illustration and explanation. It will be apparent, however, to one skilled in the art that many modifications and changes to the embodiments set forth above are possible without departing from the scope and the spirit of the invention. It is intended that the following claims be interpreted to embrace all such modifications and changes.